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DESIGN RESPONSE SPECTRA FOR AQABA CITY–JORDAN

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SUMMARY

Strong motion records for earthquakes epicentred in the Gulf of Aqaba during swarms in August 1993 and November 1995 are studied. These recordings are made at two sites in the City of Aqaba, one near the seashore and the other inland. The former site has deep alluvial profile with low shear-wave velocity, while the latter's soil profile is constituted of shallow stiff alluvium overlaying rock. The magnitudes of these events range from 4·8 to 6·2 on the Richter scale. Ground motion on the seashore site is much greater than the inland site. Response spectra are derived for each of the available accelerograms. Thirteen records at the inland site are statistically treated to arrive at mean response spectrum using 5 per cent damping. The derived spectra are found to be sharp with small plateau, this is associated with small peak displacement. Empirical site-dependent response spectra are also derived based on recent research and on recommendations of the UBC'97. Comparison is made between the empirical and measured spectra. These were found to be quite close for the inland site but data are not sufficient for the seashore site to make a conclusive comparison. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS: earthquake; seismic; response spectrum; soil amplification

INTRODUCTION

Jordan has had an earthquake code since 1985. This is in fact a part of Jordan's Code for Loads and Forces.[1] The code permits the use of equivalent static load analysis for most common building structures and requires dynamic analysis for tall and irregular buildings. It does not, however, allow for local conditions particularly as no design spectra are published in the code. The installation of strong motion recorders in Jordan and the seismic activity in Aqaba that followed are the motivation for the development of site-dependent response spectra in Aqaba. These may be derived using strong motion recordings and then compared with empirical spectra obtainable using methodology recently suggested by Borcherdt[2] and those recommended in the UBC'97.[3] Soil conditions shall clearly be reflected in those spectra particularly as response to the Aqaba 1995 earthquake showed such variance in the response at different locations within the city depending on the soil conditions at these sites.

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TECTONICS OF AQABA

The area of Aqaba is well known for its seismicity. It falls at the southern end of the 1000-km long Jordan Rift Valley. This has three main faults, the Aqaba Gulf, Wadi Araba-Dead Sea and Jordan Valley-Mount Lebanon. The Aqaba region is a part of the complex geotectonics manifested by the sea floor spreading of the Red Sea which induced a counterclockwise rotational motion of about 15° of the Arabian Block relative to the African Craton. The total displacement along the transform is estimated to be about 110 km. Of this, 60 km are postulated to be within the Gulf of Aqaba.[4]

Historic records as well as geologic records exhibit the active nature of the tectonics of Aqaba. Destructive events are reported in the years 48, 1068, 1261 and 1588 AD.[5] The City of Ayla (now Aqaba) is reported in historic records to have been totally destroyed by the earthquake of 1068 AD. Ambraseys and White[6] provide a fresh appraisal of the seismicity of the Eastern Mediterranean region in which they suggest going back to original historic sources. In their study they quote one such source as stating that a destructive earthquake occurred in Palestine in 31 BC which killed 30 000 people.

The activities of the past 30 years could be characterized by the occurrence of periodic swarms. The most significant of these are: those in 1969 lasting for 10 months and having a maximum magnitude (M_L) equal to 6·1; 1983 with maximum M_L of 5·3; 1993 with maximum M_L of 5·6 and 1995 with maximum M_L of 6·2. These magnitudes were recorded by the Jordan Seismological Observatory. Accelerograms for events since 1993 have been registered using strong motion stations, which are a part of the national network partly operational since 1991.

Many researchers have studied the seismic risk at the Aqaba area as part of risk evaluation in the Jordan Valley region. Malkawi and Fahmi[7] used the catalogue of earthquakes in Jordan and conterminous area for the period spanning 1900–1989 AD and historic records for the past two millenniums to develop ground motion attenuation relations. They arrived at the following relationship for PGA at distance R from the epicentre of an earthquake of magnitude M_s:

$$\mathrm{PGA} = 837\, \mathrm{e}^{0{\cdot}89 M_s} (R + 25)^{-1{\cdot}73} \tag{1}$$

Fahmi *et al.*[8] used this attenuation model and probabilistic seismic hazard analysis to generate PGA zoning maps for Jordan. Figure 1 shows the geographical distribution of probabilistic PGA in the Aqaba region for 50 years return period at 90 per cent probability of non-exceedance. From the figure, it can be seen that the PGA value for the city of Aqaba for a return period of 50 years with 90 per cent probability of non-exceedance is 200 cm/sec^2.[9]

EARTHQUAKE RECORDS

The strong motion network in Jordan consists of 15 stations distributed from south to north primarily along the Jordan Valley Rift. Two of these stations are placed in the Aqaba area. One is located in the Aqaba Hotel on the sea shore and the other in the Civil Defense Building up the hill about 3 km from the sea coast. Records of the 1995 earthquakes are available from both stations, while the 1993 quakes were only recorded by the Civil Defense station. Both SSA-1 three-channel digital recording strong motion accelerographs and PDR-1 accelerographs are used in the Aqaba Hotel and the Civil Defense stations.[10] The records from the two stations shall serve to compare

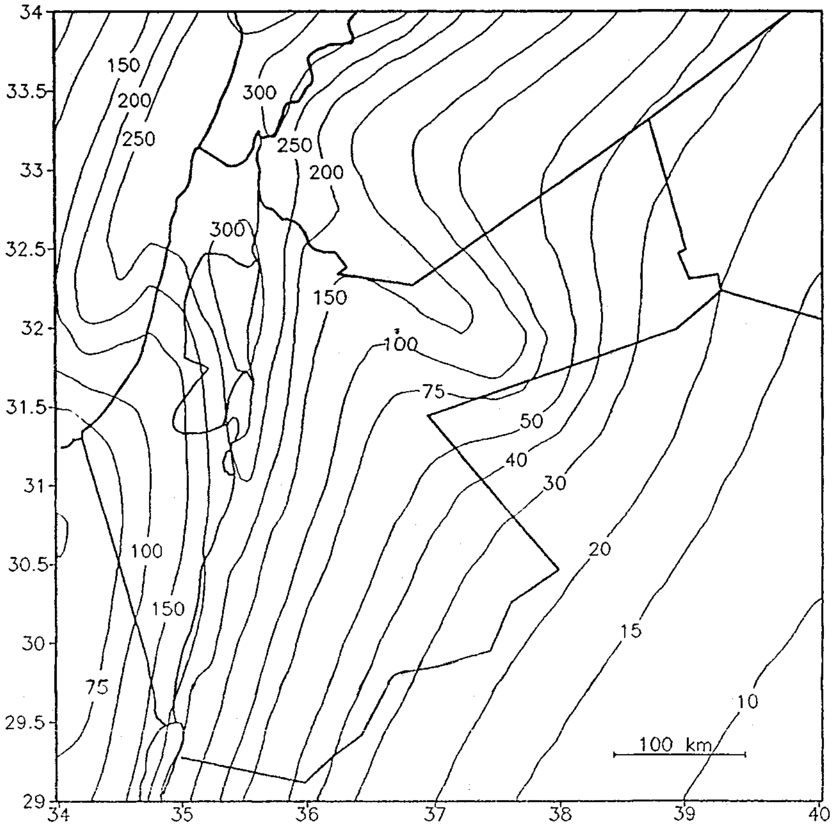

Figure 1. Maximum peak ground acceleration (cm/sec^2) with 90 per cent probability of not being exceeded in 50 Years (9)

response near the sea shore where deep medium dense alluvium layers are found with that inland where shallower and denser alluviums exist. Unfortunately, instrumentation is limited to the use of one recording device per site, which is used to register ground floor motion. No accelerograph is used to record motion on the roofs of buildings. Experience with recent earthquakes demonstrates a need to place more instrumentation to capture the complete response of buildings.[11] Furthermore, it should be noted that the measuring instruments are placed in the ground floors of the two Aqaba buildings. Studies by Crouse and McGuire[12] show that soil–structure interaction can have some significant effect on the filtering of high frequency by foundation but that this is likely to have little effect on the response spectra of motion recorded at relatively large epicentral distances as is the case here.

Table I shows basic information on the strong motion earthquakes that were recorded since 1993 and which are used in this study.

Three accelerograms are recorded for each event: two horizontal components, in Aqaba typically North–South and East–West, and one vertical. The horizontal component with the larger of the two peak accelerations is denoted L and the other S. The vertical component is denoted V. Acceleration records are integrated to get velocity and displacement records. Baseline

Table I. Strong motion earthquakes recorded at the Aqaba Hotel and the Civil Defense stations during the 1993 and 1995 swarms

Notation	Date	O.T.* H M	$M_L^\dagger$	Distance (km)	PGA $(mm/sec)^2$	Accelerograph station
C893P1	3/8/1993	12 31	4·8	112	20	Civil Defense
C893P2	3/8/1993	12 43	5·6	96	200	Civil Defense
C893P3	3/8/1993	12 54	5·4	102	118	Civil Defense
C893P4	3/8/1993	13 12	5·3	115	124	Civil Defense
C1195S5	22/11/1995	4 15	6·2	80	708	Civil Defense
C1195P6	24/11/1995	16 45	5·5	75	338	Civil Defense
C1195P7	25/11/1995	11 42	4·8	75	64	Civil Defense
C1195P8	22/11/1995	4 15	6·2	80	1568	Aqaba Hotel

* Origin time
† Magnitude

correction is made to both records. This process is carried out at the Jordan Seismological Observatory. The records of acceleration, velocity and displacement of East–West component of the horizontal motion at the Aqaba Hotel are shown in Figure 2. The time interval in the SSA-1 records is 1/200 sec and that of the PDR-1 is 1/100.

The peak values for the displacement, velocity and acceleration are placed in Table II and are examined to evaluate the main characteristics of these earthquakes.

The ratio of the Peak Ground Acceleration (PGA) of the S component to that of the L component as shown in Table II ranges from 0·71 to 0·91, while the ratio of the PGA of the vertical component to that of the L component ranges from 0·90 to 1·10. The S to L, PGA ratio is generally consistent with results obtained by Mohraz[13] who reported average values of 0·75 for motion on deep alluvium and 0·81 for that on rock. Large scatter is apparent in Mohraz data as these ratios become 0·96 and 0·99, respectively, when ratios of mean-plus-one standard deviation are considered. Table III gives the results obtained by Mohraz for 10–60 m alluvium underlain by rock. As for the V to L ratio, the values obtained from the Aqaba records seem to be high when compared with the commonly quoted value of 2/3 and the even lower value obtained by Mohraz. They are, nonetheless, consistent with recent recordings at Loma Prieta and Northridge. Bozorgnia *et al.*[14] have established that vertical-to-horizontal response spectral ratio is dependent on period and distance to site and that this ratio largely exceeds the 2/3 value.

The difference in the PGA values of the 22 November 1995 earthquake as obtained at the Civil Defense and at the Aqaba Hotel is quite evident. The ratio of the recorded PGA values is 2·2 : 1. This again is consistent with recordings elsewhere.[14,15] In analysing Little Skull Mountain earthquake of 5.6 magnitude, Su *et al.*[15] found that ground motion on alluvial sites is much larger than on rock sites, particularly at low frequencies. From power spectral densities established for the Aqaba earthquakes[16] it has been found that for the main event of 22 November 1995 the peak energy content is at about 1 Hz. This supports the high site amplification found at the seashore alluvial site.

The expected peak horizontal acceleration is the most common criterion used in seismic resistant design. However, certain response characteristics may be evaluated more readily using peak horizontal displacement or velocity. Parameters that correlate peak values of acceleration, velocity and displacement have been studied by many researchers, including: Mohraz,[13]

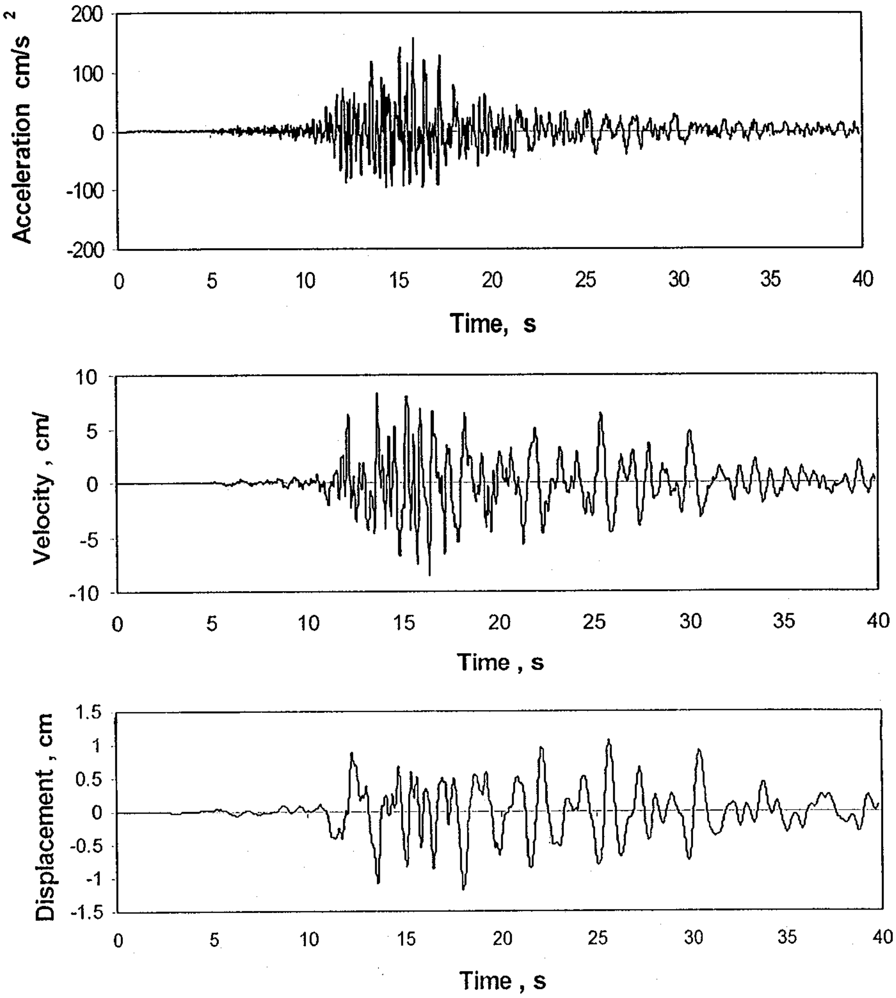

Figure 2. East–West component of the horizontal motion at the Aqaba Hotel on 22 November 1995

Newmark and Hall,[17] Newmark *et al.*[18] The ratios v/a and ad/v^2 are commonly used to describe these correlations. The notation in the previous sentence is: (a) is peak acceleration; (v) is peak velocity; and (d) is peak displacement. Values have been suggested for these parameters where no actual earthquake records are available. Those values are based on statistical data of previous earthquakes. Mohraz[13] has conducted a study of 54 earthquake records and concluded that these ratios are dependent on the soil conditions of the area. He found that v/a values are generally larger for records on alluvium than those on rock. Bearing in mind that data with wide scatter is used in the analysis, Mohraz showed that the average v/a value for rock derived from L records is equal to 610 mm/sec/g while the same for alluvium is 1219 mm/sec/g. The Aqaba records for stiff soil give an average value of 750 mm/sec/g for v/a which seems quite consistent with Mohraz's results. Seed and Idriss,[19] based on an independent study, had given v/a values of 559 mm/sec/g

Table II. Peak ground motion parameters for earthquakes recorded at Civil Defense station

EQ	Component	(a) mm/sec^2	(v) mm/sec	(d) mm	(a/g) (per cent)	$(v/a/g)$ mm/sec	(ad/v^2)	(d/a) sec^2	a_s/a_L	a_V/a_L
C893P1	$C1$	Verified data is not available								
	$C2$	Verified data is not available							NA	NA
	$C3$	20·0	1·08	0·26	0·20	534	4·38	12·7		
C893P2	$C1$	142·8	15·8	4·04	1·46	1086	2·31	27·8		
	$C2$	219·2	22·6	6·38	2·22	1013	2·72	28·5	0·71	1·1
	$C3$	199·8	22·4	4·72	2·04	1103	1·87	23·2		
C893P3	$C1$	90·2	4·46	0·48	0·92	484	2·16	5·16		
	$C2$	122·4	7·12	0·72	1·24	570	1·76	5·83	0·76	1·04
	$C3$	118·0	6·50	0·92	1·20	540	2·57	7·63		
C893P4	$C1$	91·6	3·80	0·42	0·92	406	2·67	4·49		
	$C2$	121·2	6·68	0·92	1·24	541	2·52	7·52	0·74	0·98
	$C3$	123·8	6·12	0·88	1·26	485	2·92	7·00		
C1195S5	$C1$	707·2	86·8	21·2	7·20	1205	1·99	29·5		
	$C2$	633·2	59·6	7·66	6·46	923	1·37	11·9	0·91	0·9
	$C3$	646·0	98·2	23·4	6·58	1491	1·57	35·5		
C1195P6	$C1$	258·2	9·54	0·72	2·64	362	2·03	2·71		
	$C2$	Verified Data is not available								
	$C3$	338·6	16·5	1·04	3·46	480	1·30	3·04	0·76	NA
C1195P7	$C1$	50·4	2·64	0·60	0·52	515	4·26	11·5		
	$C2$	59·4	5·16	0·56	0·60	853	1·26	9·37	0·79	94
	$C3$	63·4	4·46	0·46	0·64	690	1·48	7·17		

(a) Maximum ground acceleration
(v) Maximum ground velocity
(d) Maximum ground displacement

Table III. Ground motion ratios obtained by Mohraz (1976) for 10–60 m alluvium underlain by rock

	$(v/a/g)$ mm/sec			(ad/v^2)			a_S/a_L	a_V/a_L
	L	S	V	L	S	V		
Mean	762	914	762	5·1	3·8	7·7	0·83	0·46

for rock and 1092 mm/sec/g for alluvium. The other ratio that is used to describe ground motion peak values is ad/v^2. The average values for this ratio for the Aqaba earthquakes on stiff soil was 2·3 while Mohraz quotes values of 5·3 for rock and 3·9 for alluvium. This reflects a lower peak displacement for the Aqaba earthquakes, which has been observed in all results. The ad/v^2 ratio is a measure of the sharpness or flatness of the response spectrum with a small value being translated into a sharper spectrum and vice versa. This is evident in the sharpness of the response spectra generated for the Aqaba earthquakes. No clear correlation is found between the

magnitude of the earthquakes and the ad/v^2 ratio. From spectral density analyses,[16] however, it is found that the smaller Aqaba earthquakes possess significantly higher-frequency content.

GENERATION OF RESPONSE SPECTRA FOR AQABA 1993 AND 1995 EARTHQUAKES

A computer program was developed to calculate the elastic response spectra in terms of spectral displacement, maximum pseudo-velocity and maximum pseudo-acceleration for a user supplied seismic excitation accelerograms. The program is written in Fortran but the graphical manipulations and presentations are performed using Microsoft Excel spreadsheets. The response is calculated in a defined range of frequencies for a specific damping ratio. The program applies the numerical evaluation of the Duhamel's integration method, which is based on representing the ground acceleration as a sequence of infinitesimally short impulses. The response at time t is obtained by superimposing the response to any incremental impulse over the impulses up to that time. The technique is quite effective but has the shortcoming of being only applicable to linear and elastic systems. It also poses numerical stability problems for the particular case of high damping together with high system frequency, and long duration records. When all these parameters coincide, numerical overflow is encountered. This problem was circumvented for the purpose of the Aqaba earthquakes without any limitation on the validity of the results.

The two horizontal components of each of the 1993 and 1995 earthquakes were analysed using the developed program *RESPECT*[20] for the range of natural frequencies of 0·05–20 Hz, for damping ratios ξ of 0, 2, 5, 10, and 20 per cent. The resulting responses to all records are then normalized with respect to their basic ground motion. The pairs of numerical data for the normalized pseudo-velocity V and natural period T_n are then plotted on pre-constructed four-way logarithmic graphs.

Thirteen responses to 13 ground motion records are compiled on such a plot for the inland site. Since these are normalized, all values corresponding to a particular period of vibration T_n may be statistically analysed. Such an analysis of these data yields the probability distribution for the spectral ordinates, its mean value and the standard deviation at each period T_n. Connecting the mean values gives the mean response spectrum or the 50 percentile spectrum. Likewise connecting the mean-plus-one standard deviation values clearly gives the mean-plus-one standard deviation response spectrum or the 84·1 percentile spectrum.

The statistically generated spectra above have less jaggedness than their component spectra that are derived for one earthquake at a time. The reason is that averaging out of the peaks and troughs takes place when the mean is computed. However, even these resulting curves still exhibit strong variation in response for close periods. The use of such a response spectrum is thus not practical and is specific for the recorded earthquakes used in its generation. These curves are thus idealized by a series of straight lines producing a design response spectrum that is relevant to the site where the recorder is placed. As data for the alluvial seashore site is not sufficient, a meaningful design spectrum could only be obtained for the inland stiff site.

CHARACTERISTICS OF AQABA RESPONSE SPECTRA

Figure 3 shows, as an example, the response spectra for the 22 November 1995 earthquake as generated from the signal at the Aqaba Hotel station. Those spectra are for different damping

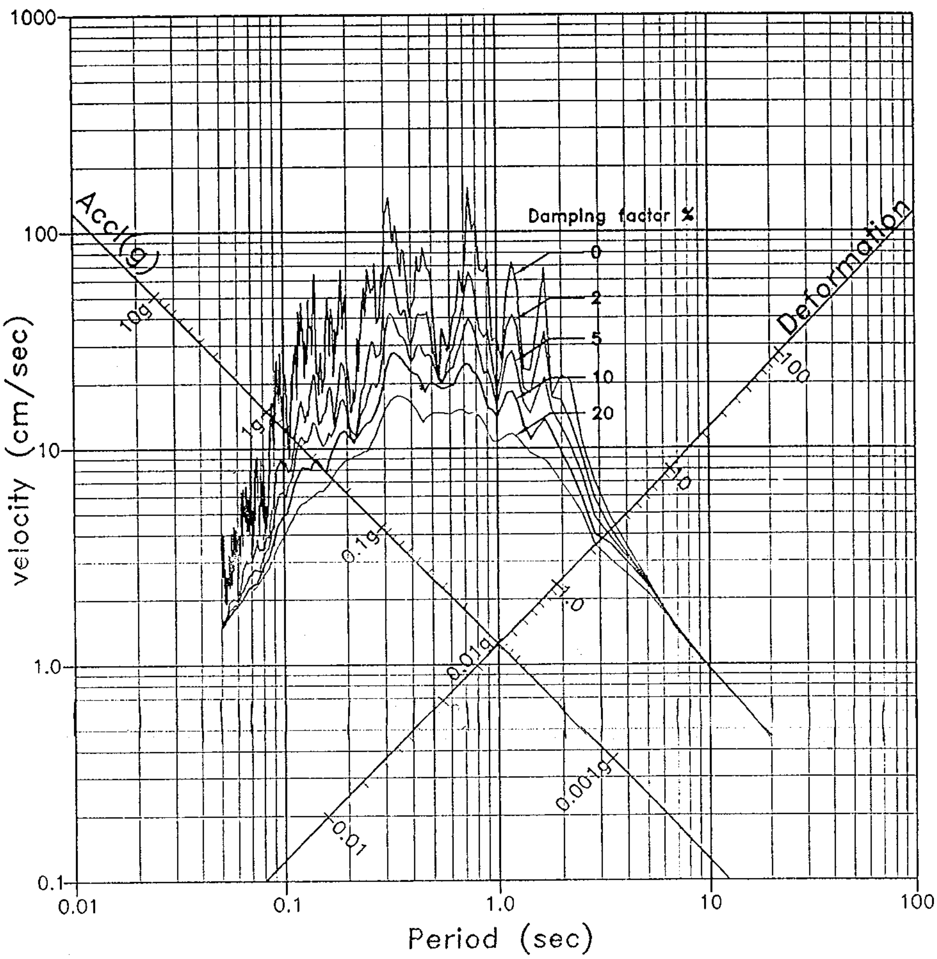

Figure 3. Response spectra for 22 November 1995 earthquake as generated from the signal at the Aqaba Hotel Station

ratios. Such a series of spectra is generated for each horizontal component of each of the recorded earthquakes. The mean response spectra, which are normalized to the maximum ground motion, are shown in Figure 4 for the earthquakes recorded at the Civil Defense station. The spectra in Figure 4 are those mean values of 13 horizontal components recorded at the Civil Defense station during the period from 1993 to 1995.

The dominant feature of all of the Aqaba earthquakes is the sharpness of the response spectra which is related to the low ad/v^2 ratio. This reflects the low value of displacement response. Another observation that may be made of the features of the Aqaba earthquakes is the rapid convergence of the displacement response to the basic ground displacement. This takes place for periods of about 10 sec. This period is smaller than Newmark's recommended value of 33 sec.

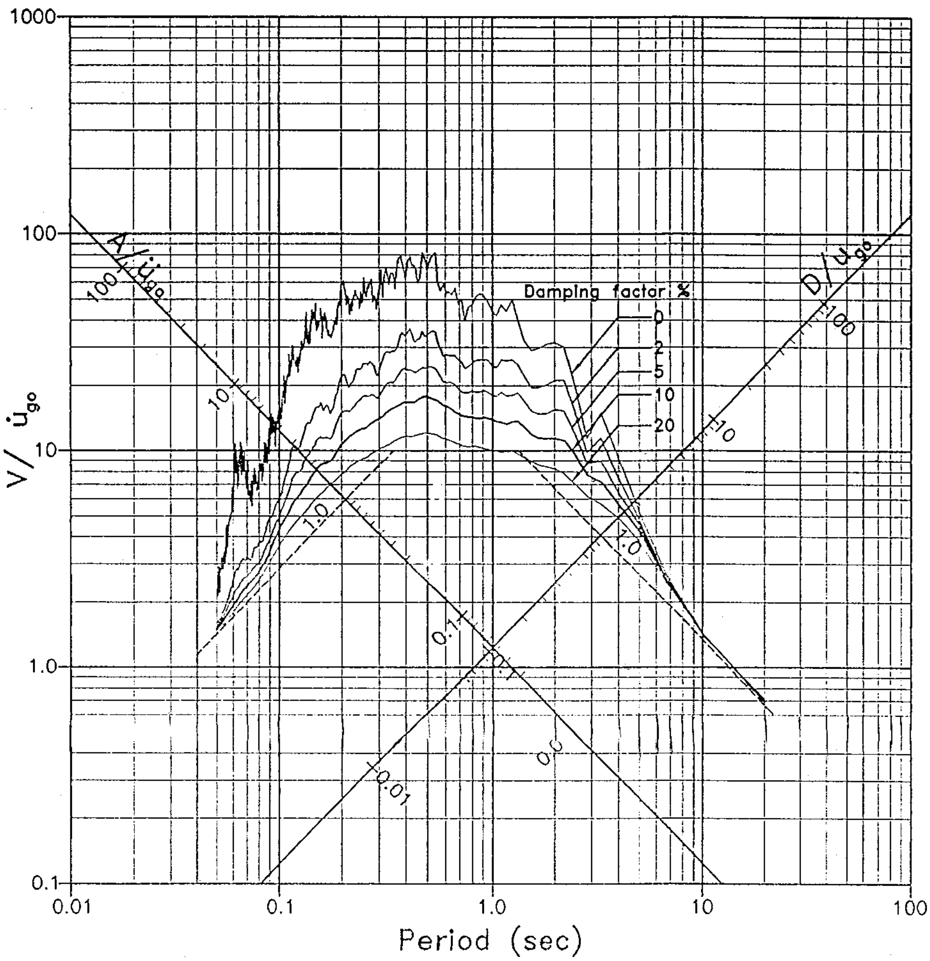

Figure 4. The mean elastic response spectra normalized to the maximum ground motion. This is obtained from 13 horizontal components recorded at the Civil Defense Station

The idealized mean response spectra are shown in Figure 5. The amplification regions are defined in Table IV and the amplification factors α_A, α_V and α_D are listed in Table V.

By comparing Newmark and Hall[17] recommended values shown in Table VI with those derived from the analysis of the Aqaba earthquakes it can be seen that good agreement exists particularly for the 84·1 percentile where more smoothening of peaks has taken place.

DESIGN SPECTRA FOR AQABA

To construct design response spectra, two approaches may be used. The first approach is to derive these from the available specific spectra generated directly from the ground motion records

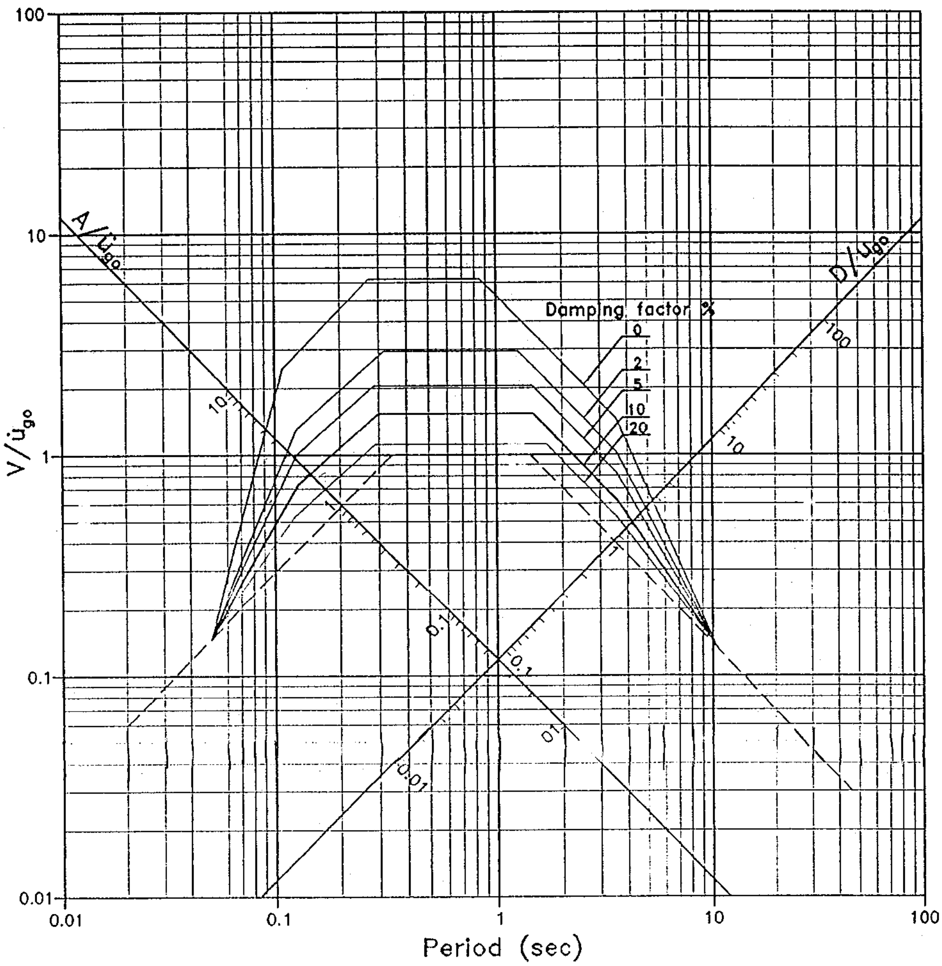

Figure 5. Idealized mean elastic response spectra normalized to the basic ground motion

Table IV. Regions of amplification for proposed idealized response spectra of Aqaba

Amplification region	Mean spectrum	Mean-plus-one spectrum
Acceleration	0·12–0·3 sec	0·1–0·27 sec
Velocity	0·3–1·5 sec	0·27–2·0 sec
Displacement	1·5–4·0 sec	1·5–3·2 sec

as discussed in the previous section. This can be in logarithmic or linear form, both shall be shown here. The second approach is to derive the sit-specific spectra purely from knowledge of soil profile without regard to the recordings made on site. The latter methodology is suggested by Borcherdt[2] for the establishment of site-dependent spectra and for code development. Based on

Table V. Amplification factors for proposed idealized response spectra of Aqaba

Damping	Amplification for mean response spectrum (50 percentile)			Amplification for mean-plus-one response spectrum (84·1 percentile)		
	$\propto_A$	$\propto_V$	$\propto_D$	$\propto_A$	$\propto_V$	$\propto_D$
0	7·0	6·2	3·7	8·1	8·9	4·2
2	3·1	3·0	2·5	3·6	3·9	3·0
5	2·2	2·0	2·0	2·7	2·8	2·2
10	2·0	1·6	1·4	2·1	2·0	2·0
20	1·2	1·1	1·1	1·3	1·4	1·4

Table VI. Amplification factors for elastic design spectra, proposed by Newmark and Hall

Damping	Amplification for mean response spectrum (50 percentile)			Amplification for mean-response spectrum (84.1 percentile)		
	$\propto_A$	$\propto_V$	$\propto_D$	$\propto_A$	$\propto_V$	$\propto_D$
1	3·21	2·31	1·82	4·38	3·38	2·73
2	2·74	2·03	1·63	3·66	2·92	2·42
5	2·12	1·65	1·59	2·71	2·30	2·01
10	1·46	1·37	1·20	1·99	1·84	1·69
20	1·17	1·08	1·01	1·26	1·37	1·38

available geotechnical data, such spectra will also be derived for the sites under study. A comparison shall then be conducted between the results of these two methods.

The response spectra are in reference to the input peak ground motion. They may be scaled to produce design response spectra based on probability maps of ground motion. If peak ground acceleration is quoted on rock then the site specific response spectrum needs to reflect soil amplification as well as response of the single-degree-of-freedom system to ground excitation.

Before generating the site-dependent spectra using available geotechnical data it is worth discussing how the Jordan code deals with the issue of soil effect and how this has developed over the years in the Uniform Building Code.

EFFECT OF SOIL PROFILE

It has always been recognized that soil conditions play a significant role in the response to seismic motion. Site response parameters in the 1991 NEHRP provisions and response spectra of UBC'94[21] were based on work by Mohraz, Seed and others in the 1970s and 1980s using seismic data recorded through 1971. Advances in knowledge and methodology were made in the 1990s, primarily as a result of the strong-motion recordings of the Loma Prieta- California earthquake

in 1989 combined with concerted effort of the scientific engineering community in interpreting the accumulating strong-motion data in the past half-century.

Site conditions have the dual effect of attenuating or amplifying the free-field ground motion and of modifying the frequency content of the motion. The level of understanding of both phenomena ranges from observation and documentation to one- and two-dimensional modelling of site response using deterministic and stochastic approaches.[22] Borcherdt[2] suggests an empirical technique for making allowance for the site effect in building code-provisions. Such an approach has since been incorporated in the UBC'97. The proposed amplification factors take into account shear-wave velocity of the top 30 m of the soil profile or other related parameters such as standard penetration or undrained shear-strength values. The site-dependent factors are also influenced by the magnitude of the design earthquake. They are estimated in two distinct ranges of the spectrum: short- and mid-period; basically allowing for increased amplification in the range of lower frequencies. This approach while being empirical, is quite rigorous and allows for quantifying the various parameters that are known to be of significance in the site amplification phenomenon.

The Jordan Code (JC) merely allows for the site-structure resonance as did the earlier versions of the UBC. Equation (2) gives the form of the soil factors in the UBC'82[23] and equation (3) quotes the soil factor δ of the JC.

$$S = a + b\,(T/T_s) - c\,(T/T_s)^2. \tag{2}$$

$$\delta = 0{\cdot}7/(T - T_s)^{1/3} \text{ and } 0{\cdot}8 < \delta < 1{\cdot}3 \tag{3}$$

where a, b and c are constants, T is the period of the structure and T_s is the period of the soil. Limits are put on the ratios S and δ, so as not to take advantage of deamplification. The value of S is lagest when T/T_s equals one, i.e. at resonance. For the situation where T is less than T_s, the code stipulates that δ should be taken as 1·3. This is found to be almost always less than the S factor of the UBC of 1982 exept for very small ratios of T/T_s, specifically where T/T_s is less than about 0·35. For the rare case of small T_s (less than 0·2) combined with a high T/T_s ratio (more than 2) δ is then also larger than S.

In the 1994 version of the UBC[21] the S factor is incorporated in a formula for C, which is the coefficient that reflects the dynamic properties of both the structure and the soil.

$$C = 1{\cdot}25\, S/T^{2/3} \tag{4}$$

S is given one of four values: 1·0 (S_1) for rock and stiff soil up to 60 m depth, 1·2 (S_2) for medium to stiff soil deeper than 60 m, 1·5 (S_3) when the soil profile contains between 6 and 12 m of soft to medium stiff clay, or 2·0 (S_4) when the depth of soft clay exceeds 12 m. When modal analysis is to be conducted, the UBC specifies three design spectra, which correspond to the first three of the four soil categories defined above. These spectra are based on work by Seed *et al.*[24] conducted on 23 earthquakes with peak ground accelerations greater than 0·05 g.

The UBC'97 applies the empirical approach previously outlined and attributed to Borcherdt. The ground-motion spectral level parameter and the amplification factor are combined in one coefficient. This coefficient is given for the short- and mid-period ranges as C_a and C_v. Code tables include values for these coefficients for five soil profile types A–E ranging from hard rock to soft soil profile. A sixth-type F is deemed to require site-specific geotechnical investigation. The soil

types are related to shear-wave velocities and a systematic numerical procedure is suggested in the code-provisions for site categorization.

EMPIRICAL SITE SPECIFIC SPECTRA FOR AQABA

The city of Aqaba is situated on alluvial fans and alluvial foundation. These are underlain by gravels made up of granitic cobbles and pebbles, which in turn overlie a sandstone formation. A more detailed geologic description of the regional geology of Aqaba is found in Rashdan.[25] Although no specific investigation was carried out to define the soil profile at the strong motion stations, data are available for nearby sites. By referring to borehole data and more recent seismic refraction testing in the area,[26] it is concluded that the near shore layers are more typical of younger less compact sediments. Using the UBC'97 methodology and shear-wave velocities inferred for the site,[16] the average shear-wave velocity for the inland site may be taken as 1370 m/sec and that for the shore-line site as 260 m/sec. These values are in turn used to construct site-dependent response spectra based on the Borcherdt approach. F_a and F_v are computed as (0·91, 0·84) and (1·63, 2·48) for the shore and inland sites, respectively. These factors are in reference to soil-type SC-Ib as defined by Borcherdt which is equivalent to type B of the UBC'97. Site response spectra are then constructed and are produced in Figure 6. These are normalized to peak ground acceleration but are based on 0·1 g. The latter is used in the evaluation of the

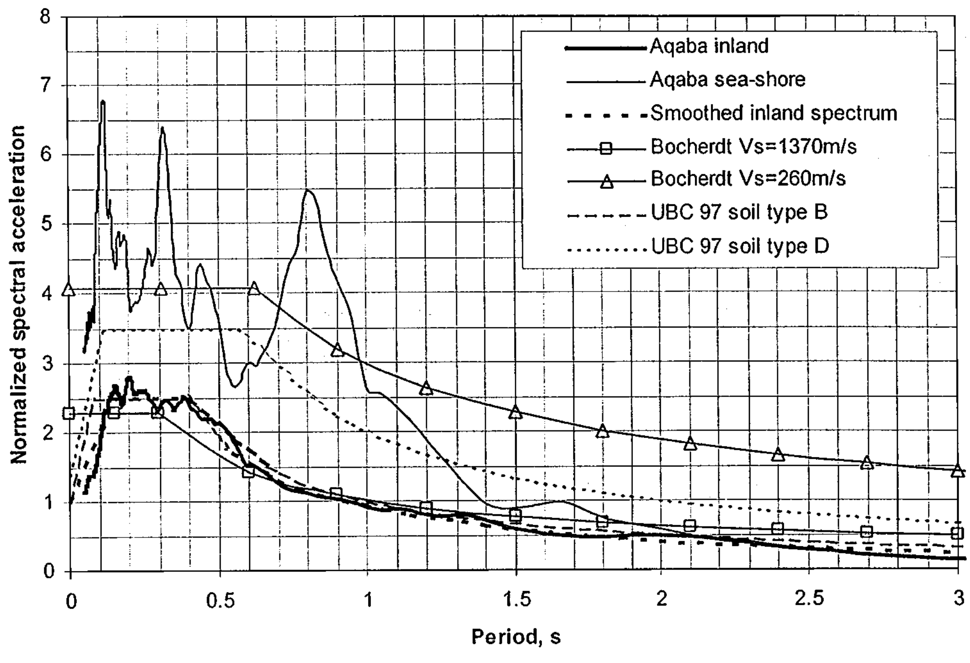

Figure 6. Response spectra based on ground motion recordings, empirical approach after Borcherdt (2) and UBC'97 recommendations

amplification factors using

$$F_a(v, I) = (v_0/v)^{ma} \tag{5a}$$

$$F_v(v, I) = (v_0/v)^{mv} \tag{5b}$$

where I is the ground acceleration and is taken as 0.1 g, v_0 is the reference shear-wave velocity and is taken as 105 m/sec and finally m_a and m_v are dependent on I and soil profile type and are taken as 0·35 and 0·65, respectively.

The seashore and inland sites are found to be closest to soil profile types D and B, respectively, as defined in UBC'97. The design response spectra are thus derived for these two types and are also plotted in Figure 6.

COMPARISON BETWEEN MEASURED AND EMPIRICAL SPECTRA

For the purpose of comparison the means of the normalized response for 5 per cent damping are plotted for the inland and seashore sites in Figure 6. Because of the availability of 13 records smoothening is meaningful and is thus performed for the inland site. It should be noted that the seashore site response is scaled to reflect the increased free-field acceleration as compared to the inland site. To obtain a specific response value, all curves in Figure 6 need to be scaled using expected ground acceleration on a site similar to type B as defined by UBC'97.

The measured spectra for the inland site are clearly consistent with the empirical spectra by Borcherdt and UBC'97 type B. The latter has marginally larger values for short periods due to the fact that the Borcherdt curve is computed for the site-specific shear-wave velocity, which is at the upper limit of type B range. The UBC'97 curve drops more rapidly beyond the plateau as it assumes a period exponent of unity as opposed to the 2/3 incorporated in the Borcherdt response. As for the seashore site, the measured spectrum is based on merely two records and thus contains event particular peaks. A crude leveling of the peaks and troughs shows general agreement with Borcherdt empirical spectrum for the 260 m/sec shear-wave velocity site in the short-period range. The notable observation about this measured spectrum is the rapid decline of response ordinates beyond the one-second range.

CONCLUSIONS

Based on the study of a number of earthquakes measured at two sites in the City of Aqaba, response spectra were generated. In all, eight earthquakes with magnitudes ranging from 4·8 to 6·2 and which occurred in the period between 1993 and 1995 were investigated. The earthquakes gave a relatively low displacement response and sharp response spectrum, which exhibits a short velocity plateau. The ratio of vertical-to-horizontal motion of all recorded events significantly exceeds 2/3, which is noted to be consistent with recent recordings elsewhere. Peak ground motion at the seashore alluvial site was much larger than that inland. The current Jordan Code does not properly allow for the site amplification and requires revision. The response spectra generated from records made on the inland stiff site are found to compare well with those recommended by UBC'97. Even though data are not sufficient for the seashore site, comparison using available data reveals consistency with UBC's treatment of the soil factor.

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